

Article

Real Driving Emissions in Extended Driving Conditions

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Abstract: The real driving emission (RDE) testing for certification of vehicles is performed in conditions that are well defined in legislation. For emissions inventories and for research, the influences of some extended driving conditions on emissions are an interesting issue. In the present work, some examples of RDE results from two common passenger cars with gasoline and diesel propulsion are given. The varying driving conditions were “winter/summer”, “mild/aggressive”, and “higher altitude/slop”. The driving conditions: “winter”, “aggressive”, and “higher slope/altitude” generally require more energy, cause higher fuel consumption, and therefore, higher CO₂-emissions. The condition of “winter driving”, especially in the urban type of operation, may cause some longer phases with not enough warmed-up exhaust aftertreatment and consequently some increased gaseous emissions. The DPF eliminates the nanoparticles (PN) independently on the driving conditions. Nevertheless, the DPF regeneration has an influence on the CO₂-normality of the trip. The CO₂-normality primary tolerance range can also be exceeded with aggressive driving. The elaborated results confirm the usefulness of the existing legal limits for the driving conditions of RDE homologation tests.

Keywords: emissions at cold start; warm-up; RDE; portion of idling; stop & go



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1. Introduction

The testing and evaluating of real driving emissions (RDE) as a part of the certification of new types of passenger cars was introduced into EU-legislation in September 2017. Different details concerning the development and refining of testing procedure, testing equipment, evaluation, and others were introduced in so-called RDE packages. The fourth RDE package applies for certification since January 2019. The most important innovations and amendments of RDE4 vs. RDE3 concern [1]:

- Specifications and calibration of PEMS components and signals.
- Verification of overall trip dynamics with MAW (moving average windows) and with RPA (relative positive acceleration).
- Determination of the cumulative positive elevation gain of a PEMS trip.
- Calculation of final RDE emissions.
- Data exchange and reporting requirements.
- Provisions for in-service-conformity (ISC).

Great importance was attached to in-service-conformity (ISC) testing and reporting (article 9). The responsibility for ISC is shifted to granting type approval authorities (GTAA's), external specialized laboratories, or technical services. Extensive useful information about the application of the RDE packages can be found in specific literature and on the internet [2–7]. Collection of RDE-data offers several synergies. The increased amount of RDE-data can be used for different objectives, such as: further development of emission inventories, compliance with “In-Service Conformity” (ISC, EU regulation 2018/1832), and market surveillance activities (EU regulation 2018/858). Emission factors and emission inventories are an important source of data for compiling and modelling the emissions

of traffic in different situations. There is in the EU, continuous work and development of emission data inventories [8–12].

Extensive activities of testing RDE by means of PEMS (portable emissions measuring systems) have been performed in recent years, aiming not only at emissions, but also the improvements of instrumentation, of testing procedures, and of evaluation [13–23]. The test for certification purposes have to be performed in driving conditions, like ambient temperature, altitude, or driving dynamics, which are defined in the regulations according to the most commonly appearing ranges. For emissions inventories, some other (extended) driving conditions are of interest. Therefore, several studies have tried to determine the influence of boundary conditions such as ambient temperature (winter/summer). Driving style (aggressive/mild) as well as the influence of slope and geodesic height. These different factors were addressed by the authors in [23–30]. The entirety of these factors will now be presented in the present paper to give some examples of influences of the extended driving conditions on the emissions and on the (certification) validity of the trip for two typical passenger cars (gasoline and diesel). The tests were performed by the Laboratory for Exhaust Emissions Control (AFHB) of the Berne University of Applied Sciences (BFH-TI), Biel-Bienne, Switzerland.

2. Testing Material, Means, and Methods

2.1. Test Vehicles and Used Gas PEMS and PN PEMS

The tests with extended driving conditions were performed on two vehicles V1 (Gasoline Euro 5) and V2 (Diesel Euro 6). The most important data of these vehicles are listed in Table 1.

Table 1. Data of the vehicles used for the comparison tests.

Name	Type	Model	Fuel	EATS	Displ.	Power		
-	-	Year	-	-	ccm	kW		
V1	LDV	PC	2012	Gasoline	Euro 5a	3WC	1.596	132
V2	LDV	PC	2017	Diesel	Euro 6b	DPF + SCR	1.968	110

All vehicles were operated with the Swiss market fuels and with lubricating oils, which were present in each vehicle.

2.2. Gas PEMS and PN PEMS

For measurements of gaseous components, the system Horiba PEMS OBS-ONE was used. The most important data of this GasPEMS system are given in the Table 2. As PN PEMS for Real Driving Emissions two systems were used:


- Horiba OBS-ONE PN measurement system (OBS-PN). This analyzer works on the condensation particles counter (CPC) principle, has an integrated sample conditioning system (double dilution and catalytic stripper ViPR, 350 °C), and it indicates the summary PN concentrations in the size range 23 to approximately 1000 nm.
- NanoMet3 from TESTO (NM3). This analyzer works on diffusion charging (DC) principle, has an integrated sample conditioning system, and it indicates the solid particle number concentration and geometric mean diameter in the size range 10–700 nm.

For the exhaust gas sampling and conditioning of the NM3 a ViPR system (ViPR . . . volatile particle remover) from Matter Aerosol was used. This system contains:

- Primary dilution—MD19 tunable rotating disk diluter (Matter Eng. MD19-2E).
- Secondary dilution—dilution of the primary diluted and thermally conditioned sample gas on the outlet of evaporative tube.
- Thermoconditioner (TC)—sample heating at 300 °C.

Both PN PEMS present several advantages like compactness, robustness, fast on-line response and both are recognized for legal testing purposes.

Table 2. Data of the applied GasPEMS.

Gas PEMS	
	
Instruments	Horiba PEMS OBS-ONE
Exhaust concentrations	CO ₂ , CO, NO _x , NO ₂ , THC
Measurement principle	heated NDIR *, CLD, heated line
Engine parameters	OBD
Vehicle speed and position	GPS
Exhaust flow	EFM
Ambient parameters	p, T, H
Electrical power	>300 W (>800 W with FID and PN)
Dimensions	500 × 500 × 500 mm +Pitot tube +heated line +batteries

* OBS one: H₂O is monitored to compensate the H₂O interference on CO and CO₂ sample cell heated to 60 °C.

2.3. Test Procedures

The RDE tests were performed on the road in real driving conditions. For all tests, except of higher slope/altitude the standard and legally valid AFHB-route was used. (More information about the routes with higher slope/altitude is given in the “results”). All tests were started with cold engine. The ambient temperatures were in the range of 20 °C, except of the winter attempts with t_{amb} in the range of 5 °C.

The evaluation of data was performed according to the legal requirements with EMROAD program, package RDE 4.

3. Results

3.1. Winter/Summer Conditions

Figure 1 shows an example of cumulated RDE results obtained with the gasoline vehicle (V1) in winter driving conditions. There were, respectively, three repetitions performed on the official RDE-circuit. Some emissions differences between the repeated tests are caused by different traffic situations and driving behavior. Especially stronger accelerations, mainly in the urban part, can produce higher emissions increments.

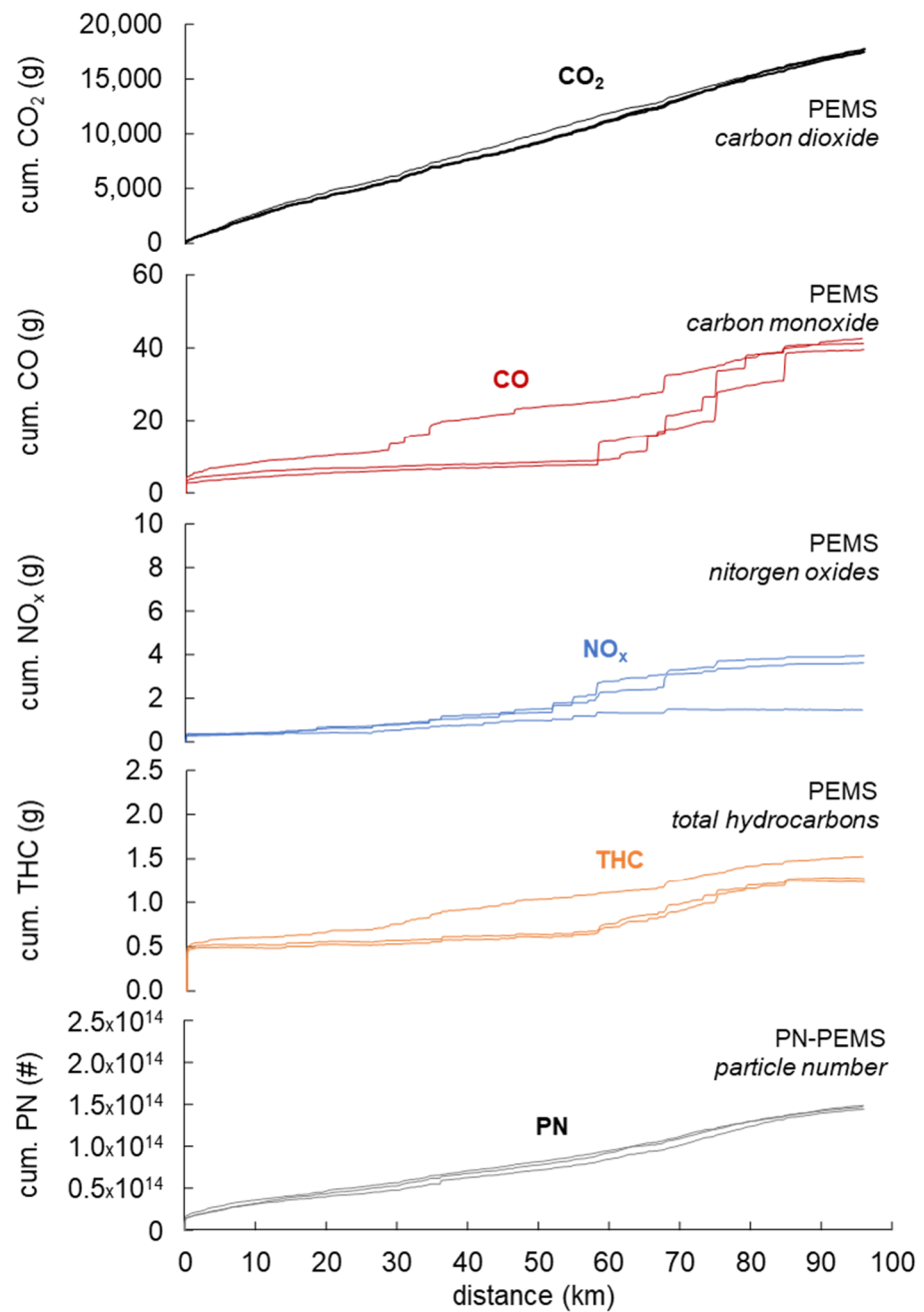


Figure 1. Example of cumulated emissions in winter, official RDE route, vehicle 1, gasoline.

Figure 2 summarizes and compares the results of the gasoline vehicle (V1). Considering the averages of three repetitions, it can be followed that in winter conditions, there are higher values of CO₂ and CO in the total trip. For NO_x and PN, there are no significant differences. There are unfortunately no measured values for THC. However, according to the general experience, the tendencies of HC are in line with the tendencies of CO. The winter in the season 2019/2020 was quite mild with the ambient day temperatures around 5 °C. Figure 3 shows an example of cumulated RDE results obtained with the diesel vehicle (V2) in summer driving conditions.

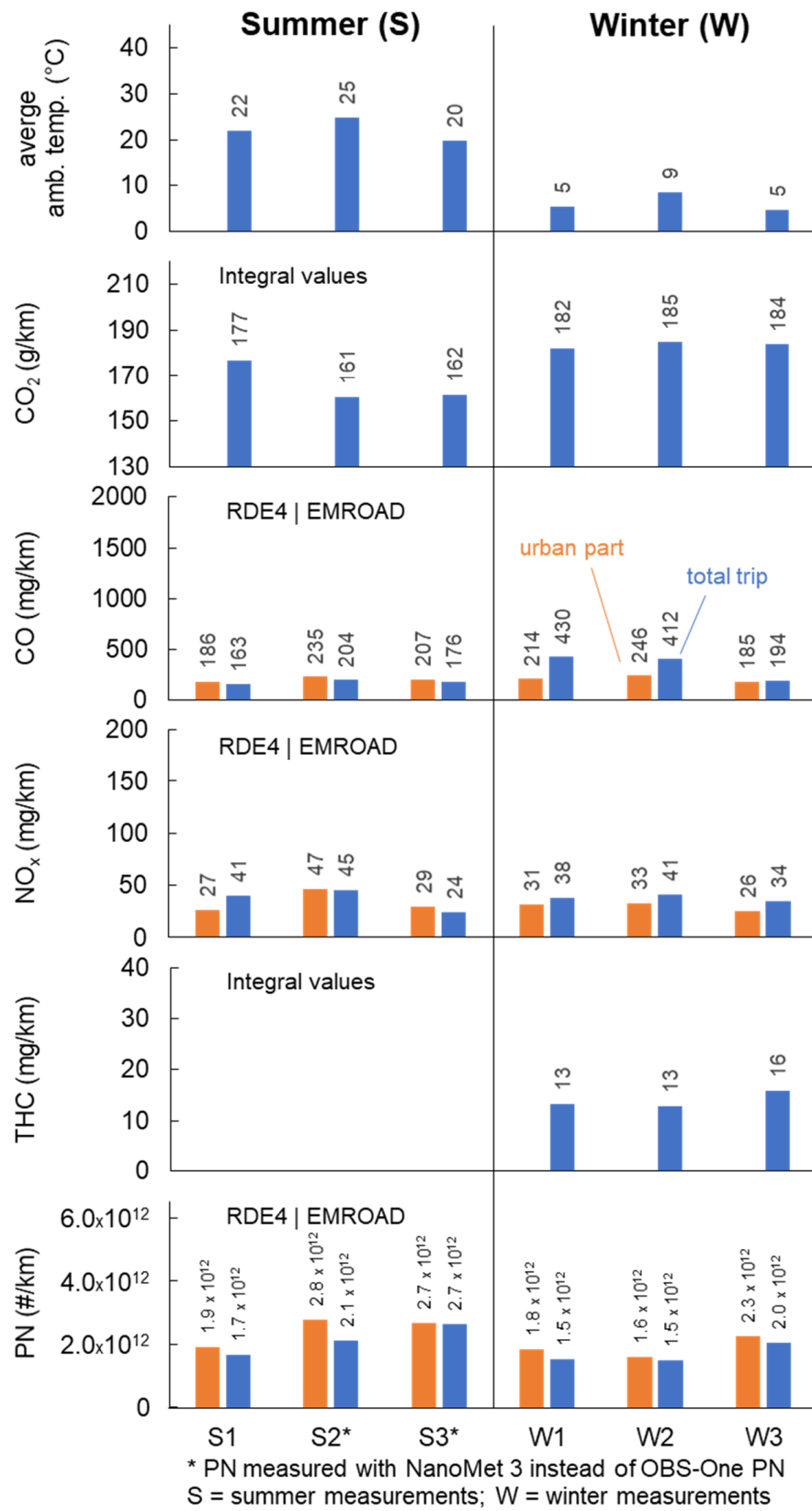


Figure 2. Comparison of real driving emissions in summer and winter conditions, official RDE route, integral average values, vehicle 1, gasoline.

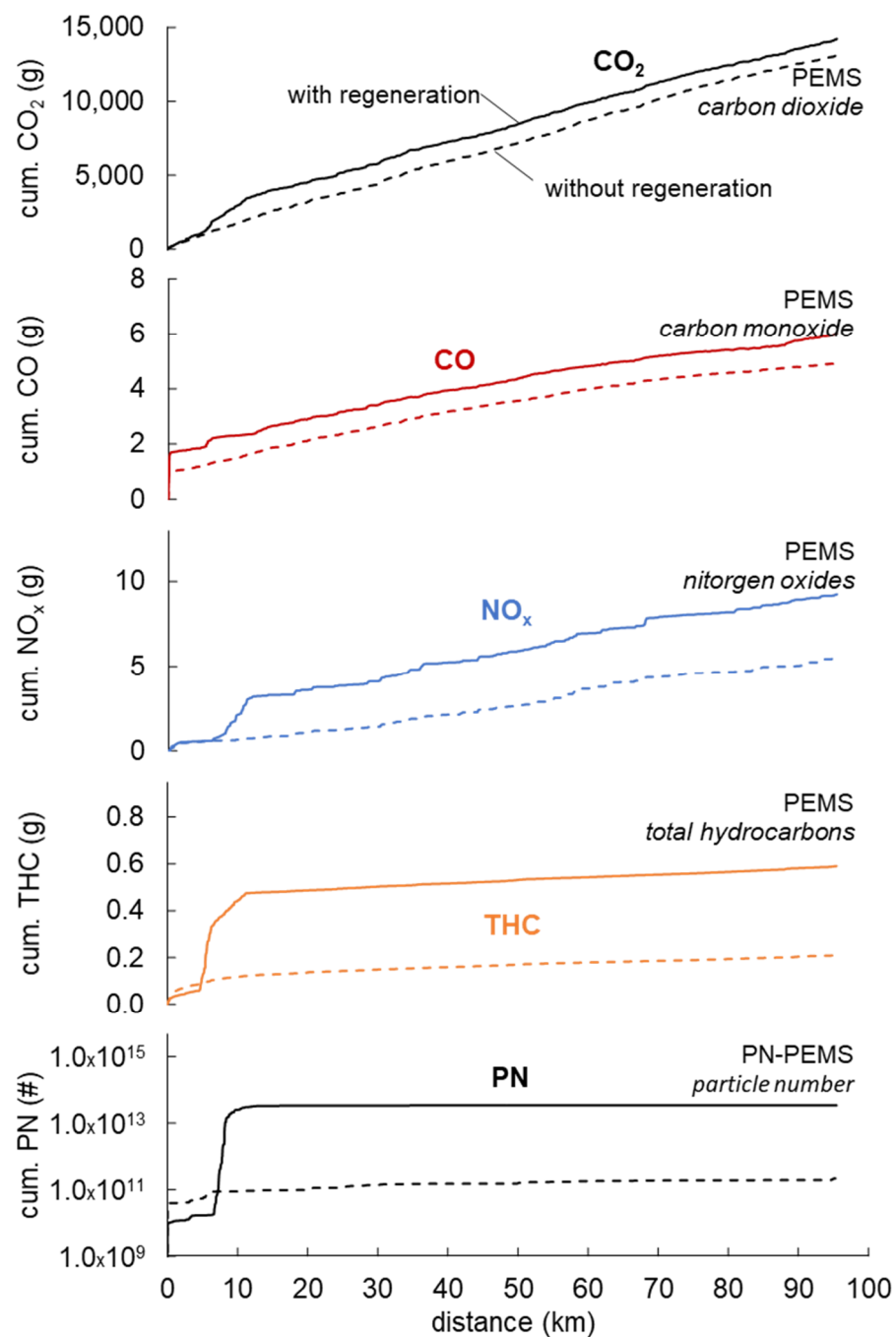


Figure 3. Example of cumulated emissions of the diesel, vehicle 2, in summer with DPF regeneration, official RDE route.

In both test series (summer and winter), one of the repetitions was with DPF regeneration, which was ordinarily triggered by the electronic control system of the vehicle. The plots “with regeneration” are here presented, together with one of the trials “without regeneration”. The regeneration increases clearly the represented emissions. Figure 4 summarizes and compares the results of the diesel vehicle (V2). Considering the averages of the three repetitions, it can be remarked that the winter-operation increases slightly the CO_2 - and NO_x -values. The levels of CO, THC, and PN stay unchanged. The regeneration increases clearly (both in summer and in winter tests) CO_2 -, NO_x -, and PN-values. There are no visible effects on CO and very slight increase of THC, which, being at a very low absolute level, may be considered as insignificant. It can be stated that in these testing

conditions of a quite mild winter period, the effect of regeneration on several emission components is stronger than the effect of the lower ambient temperature of the winter driving conditions. The fact of increased emissions (especially PN and NO_x) during the DPF regeneration is well known and the type approval legislation considers it adequately by averaging the regeneration cycles with the non-regeneration ones.

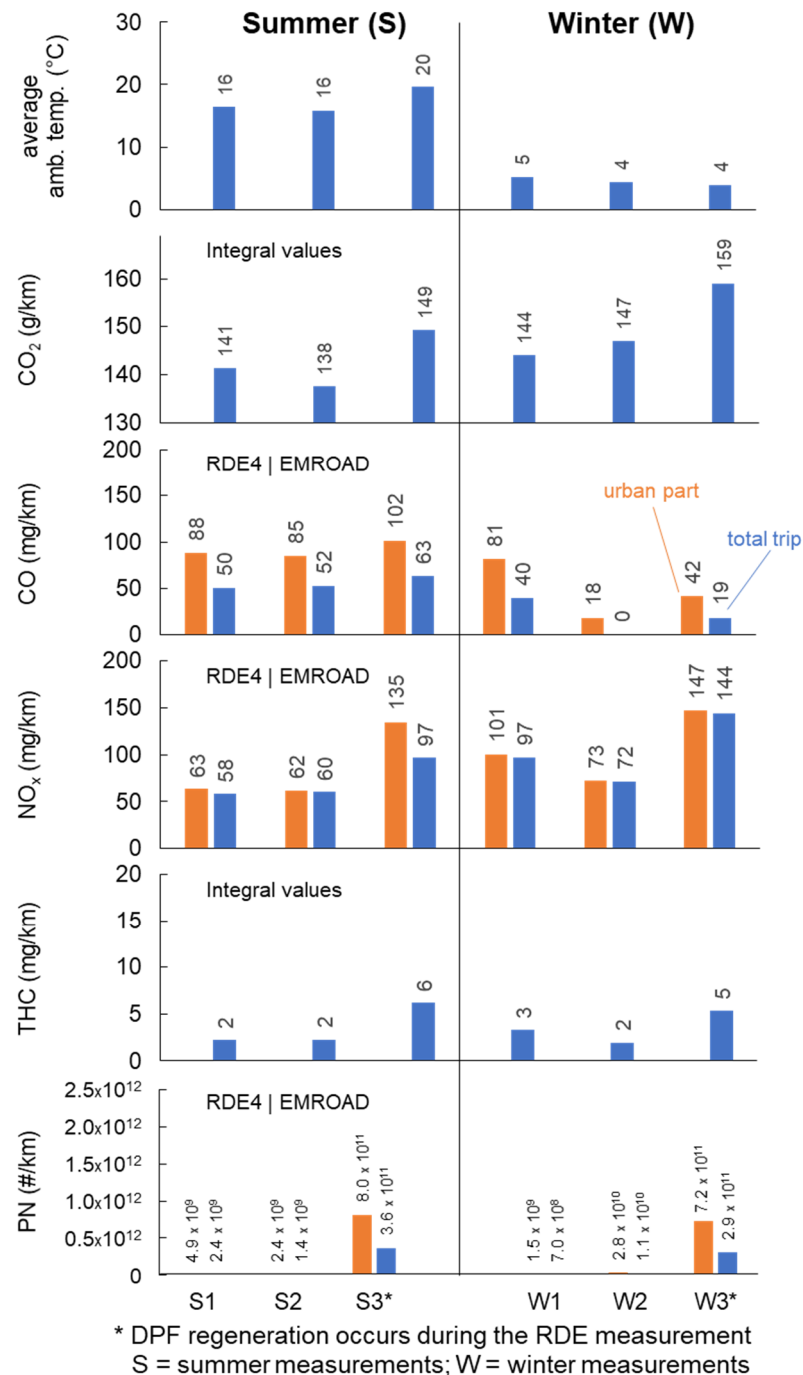


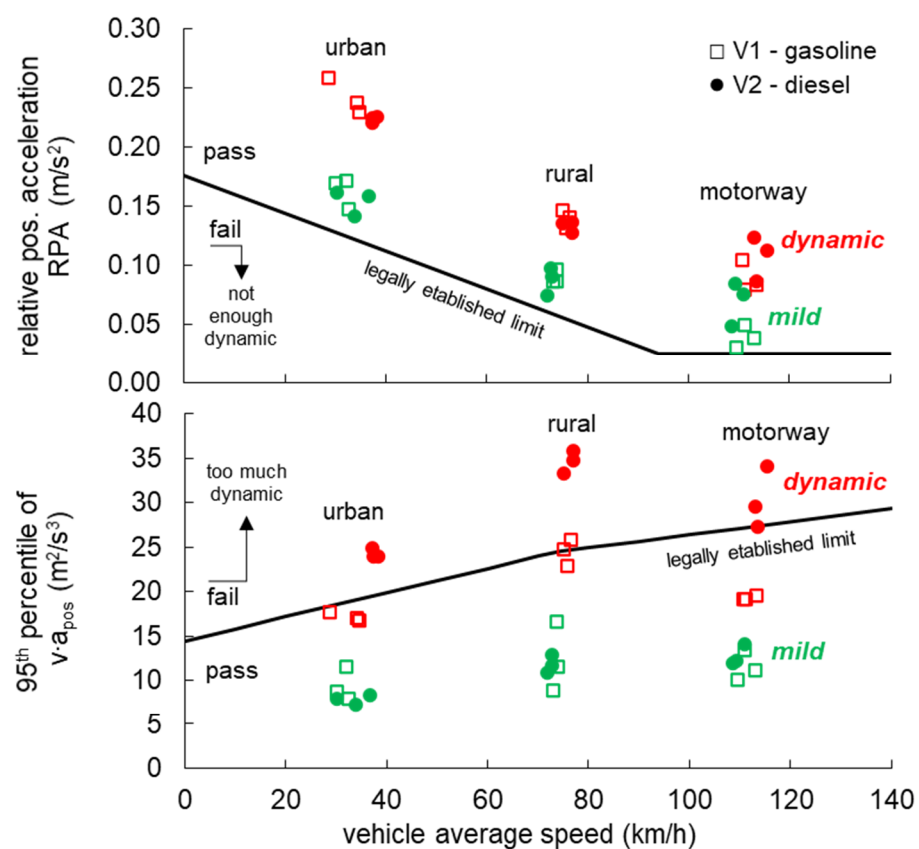
Figure 4. Comparison of real driving emissions in summer and winter conditions, official RDE route, integral average values, vehicle 2, diesel.

3.2. Mild/Aggressive Driving

For each vehicle and each variant of driving style, three tests were performed. Figure 5 represents the validity check of driving dynamics for both vehicles. In the top part of the figure, the definition and the legal limit line of the relative positive acceleration (RPA)

are given. All results are in the domain “pass”, i.e., the check, if the trip dynamics is not too weak, is fulfilled. In the bottom part of the figure, the legal limit line of [95% of $v \cdot a_{pos}$] is represented. The domain “fail” means that there are a too hard driving behavior and excessive dynamics of the trip. This is the case for aggressive driving style with the diesel vehicle (this type of vehicles is constructed and well-known for the high torque characteristics at lower engine speeds). It can be concluded that:

- The mild and dynamic driving styles have clearly different parameters of the RPA and ($v \cdot a_{pos}$); both parameters are higher for aggressive driving.
- During road driving, the parameters of the RPA and ($v \cdot a_{pos}$) are for each variant of vehicle and driving style quite repetitive.
- With the diesel vehicle, an excessive driving dynamic, beyond the legal acceptance, was realized.



$$RPA_k = \sum_j (\Delta t \cdot (v \cdot a_{pos})_{j,k}) / \sum_i d_{i,k}$$

v : vehicle speed; a_{pos} : positive acceleration, d_i : distance, k : for urban, rural or motorway shares

Figure 5. Influences of mild and dynamic driving styles on RDE trip validity for RPA and 95th percentile of $v \times a_{pos}$, vehicle 1, gasoline, and vehicle 2, diesel.

Figure 6 shows the CO₂-normality check for both vehicles. The normality check that is the comparison of CO₂ emissions during the RDE-measurement using MAW with the reference CO₂-emissions obtained on the chassis dyno during the WLTC. For the gasoline vehicle (in the top part of the figure), there are clearly higher CO₂-values at dynamic driving, but the trips and their dynamic conditions are entirely normal since the characteristic curves are not exceeding the primary tolerance band of +45(40)/−25% (of the average WLTC-CO₂-values). The CO₂-normality check for diesel vehicle is represented

in the bottom part of the figure. In the highest speed range and with “mild” operation, the characteristic line exceeds the primary tolerance domain $+45(40)/-25\%$. In one of the trials with “mild” operation, DPF regeneration happened. This had consequences on CO_2 -values and caused them to exceed the primary tolerance band as well at the lowest speed range. It can be concluded that:

- The driving style has an influence on the CO_2 -normality.
- The normality check is also passed with the dynamic driving style.
- The DPF regeneration (diesel) has an influence on the CO_2 -normality, which may cause the check to fail.

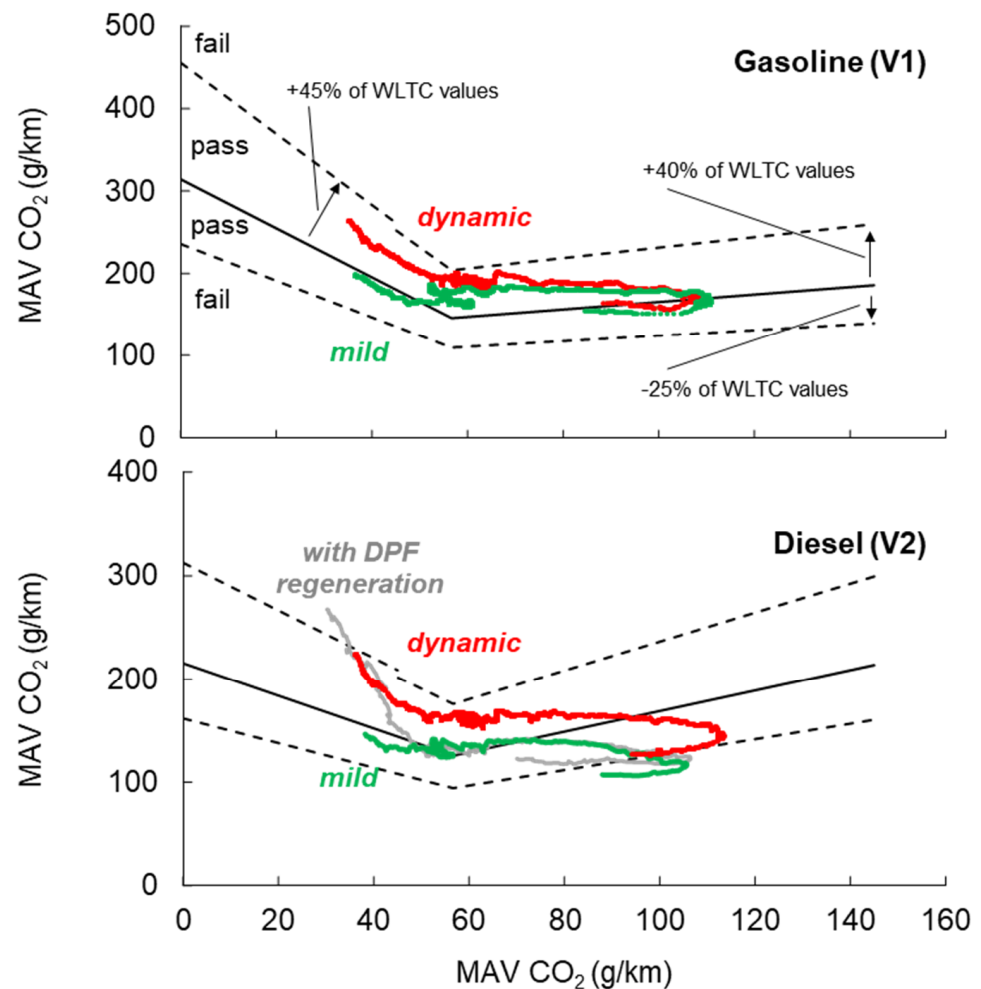


Figure 6. Influences of the driving style on CO_2 emissions for normality check for vehicle 1, gasoline, and vehicle 2, diesel.

Figure 7 represents the influences of driving style on the cumulated emissions of CO , NO_x , CO_2 , and PN of the gasoline car for, respectively, three “mild” and “dynamic” tests. The following relationships can be remarked:

- The driving style has a very strong influence on CO -emissions and the results from the three tests are quite repetitive (except for highway).
- The driving style also influences strongly the NO_x -emissions during cold start and city part; in case of aggressive driving in the urban part, the NO_x -values scatter vary much which also explains the large differences of cumulated NO_x with the “dynamic” driving.
- The “dynamic” driving requires more energy, causes higher fuel consumption, and, therefore, higher CO_2 -emissions.

- There is no visible effect of driving style on the PN-emissions, the absolute values in (#/km) for this GDI-vehicle, without GPF are quite high, above the legal limit of 6×10^{11} (#/km).

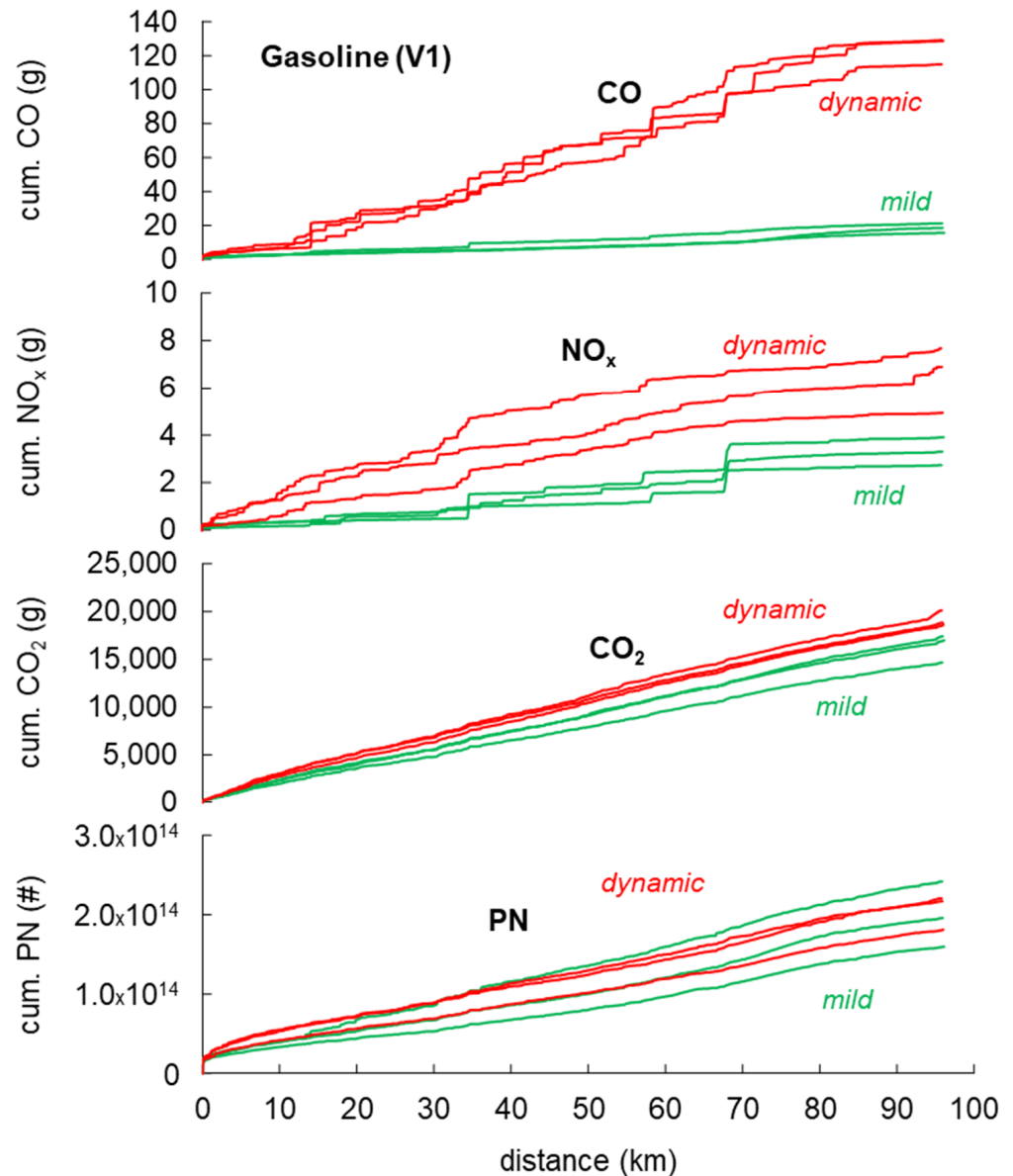


Figure 7. Influences of the driving style on the cumulated emissions of the gasoline vehicle (V1).

Figure 8 shows the influences of the driving style on the cumulated emissions of CO, NO_x, CO₂, and PN of the diesel car. The logic of the representation is the same as in Figure 7. The following relationships of emissions can be remarked for this vehicle V2:

- The CO-emissions are very low and they are independent of the driving style.
- All other emissions of NO_x, CO₂, and PN are clearly increased by the dynamic driving style.

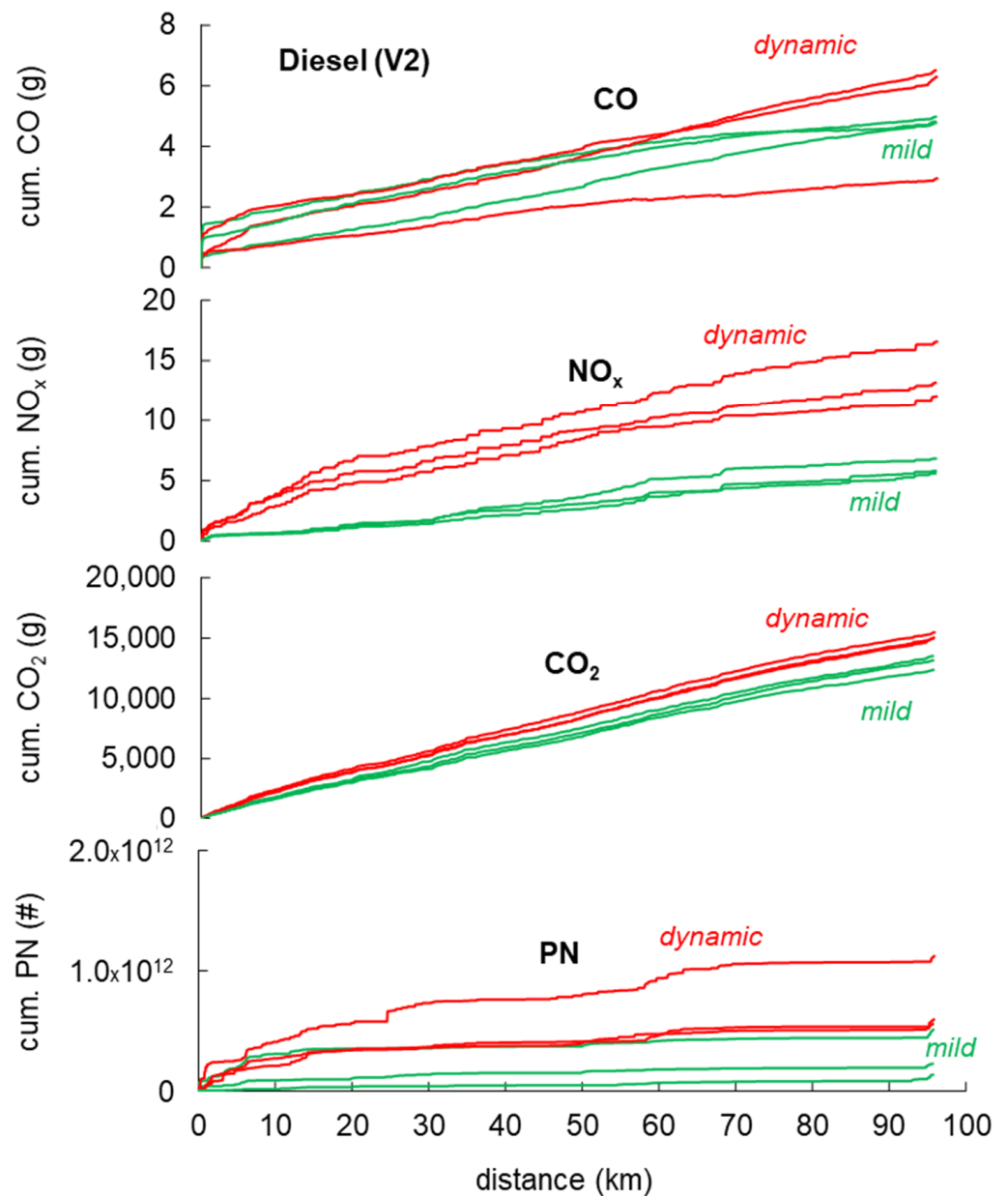


Figure 8. Influences of the driving style on the cumulated emissions of the diesel vehicle (V2).

A rough comparison of emissions of both test vehicles (V1 gasoline Euro 5 and V2 Diesel Euro 6) shows the same typical proportions: higher CO, higher CO₂, and higher PN (*w/o* GPF) values for gasoline V1; higher NO_x and lower PN (with DPF) for diesel V2. Figure 9 summarizes the variations of the emissions in (%) between mild and dynamic driving style. The higher variations of NO_x and CO₂ in the urban part can be generalized as an effect of higher dynamics in city driving. The very high variations of CO of the gasoline car (especially in the rural- and highway parts) must be considered as specific for this vehicle. They certainly could be changed by the measures lowering these emissions (CO) of this vehicle. The PN-emissions of the diesel vehicle are at a very low level (due to DPF) and the driving style has a stronger percentual influence than with the gasoline vehicle (GDI *w/o* GPF).

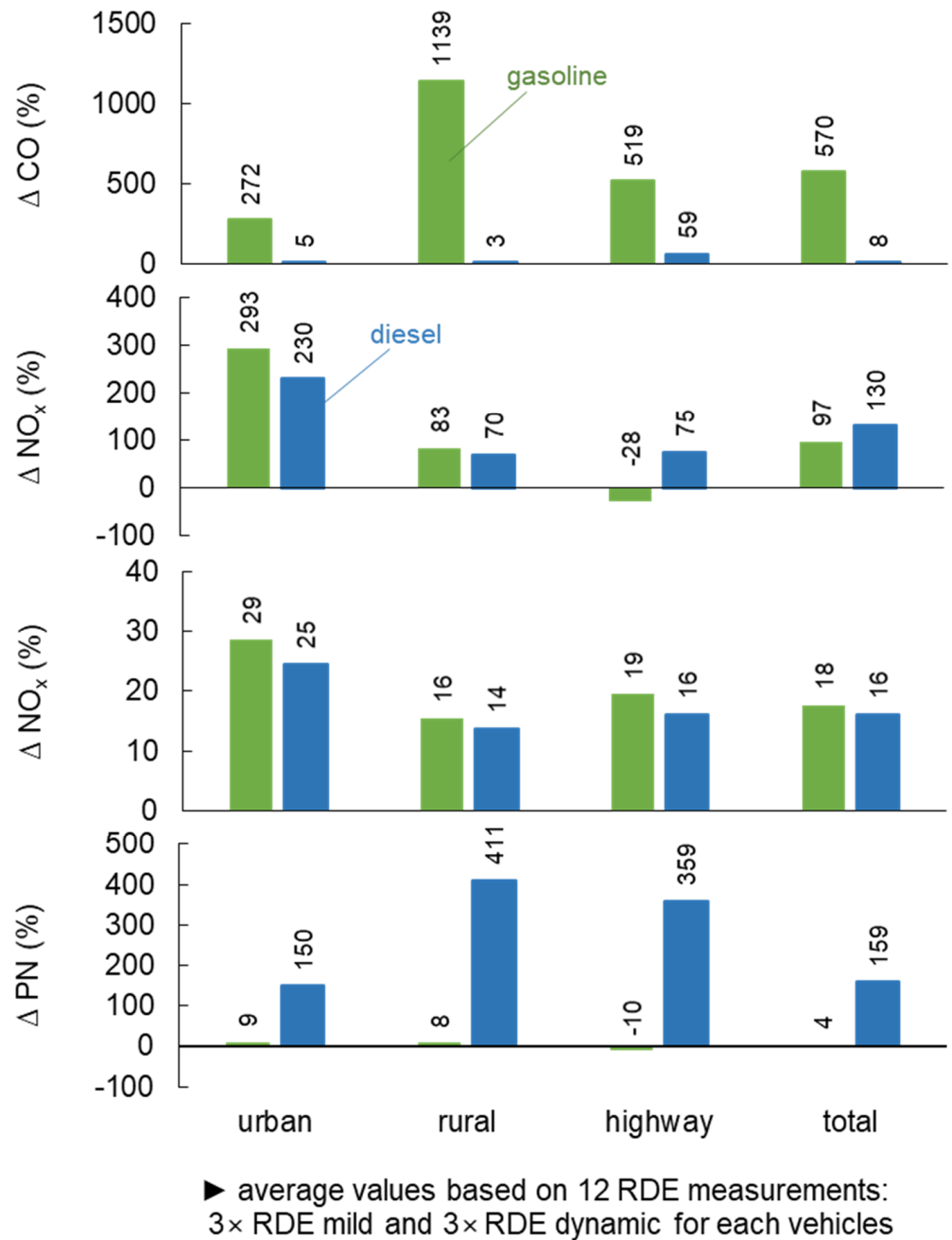


Figure 9. Variations of RDE between the mild and the dynamic driving styles, vehicle 1, gasoline and vehicle 2, diesel.

3.3. Higher Slope/Altitude

In this working package, the results obtained on a normal legally valid circle were compared with two other “high altitude” circles. The normal route is called in further diagrams as “cir1”. The other two routes are: RDE route with higher altitude variations, “cir2” (Pierre-Pertuis, Tavannes), and RDE route at high altitude, “cir3” (plateau de Diesse). Examples of the speed profiles and the traces of altitude of these test circuits are illustrated in Figure 10.

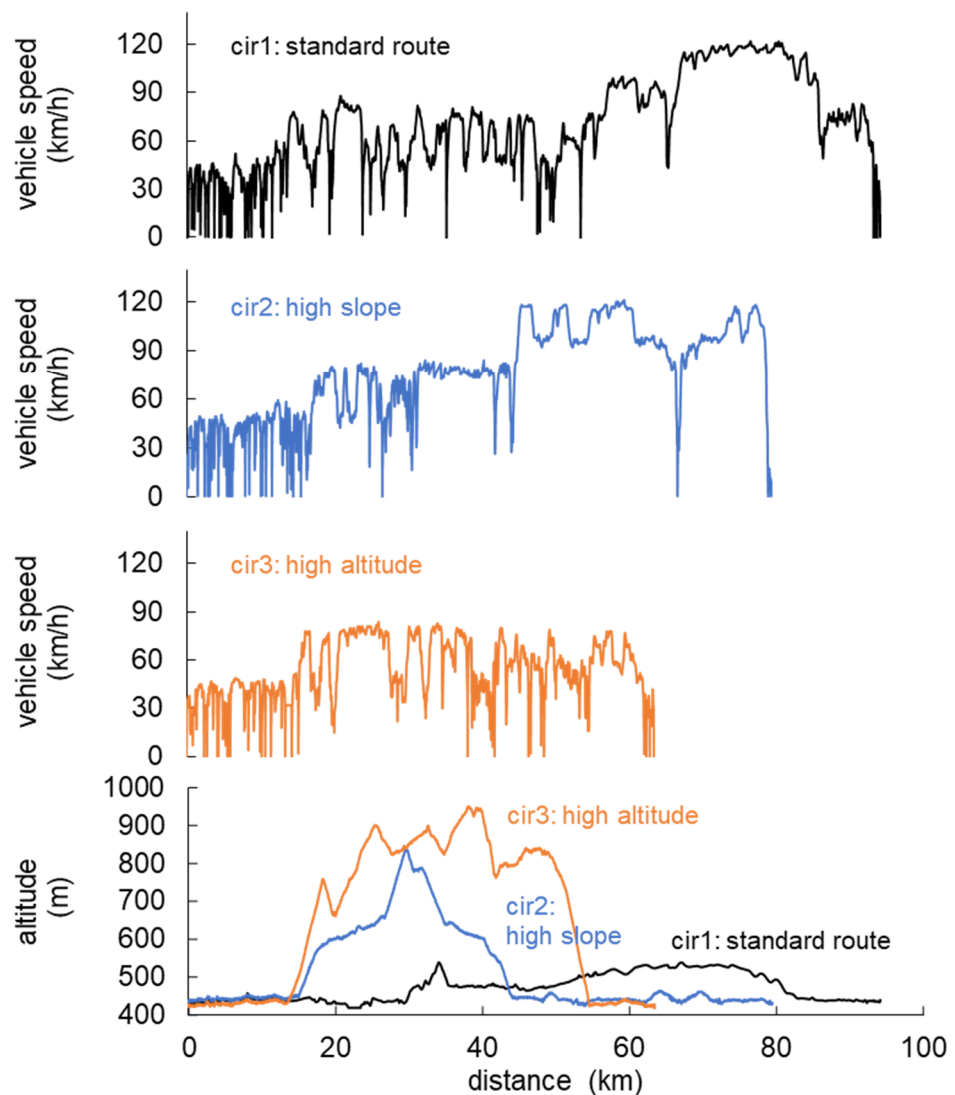


Figure 10. Speed and altitude profiles of the used test circuits: cir1-standard route, cir2-high slope, cir3-high altitude, gasoline (V1).

These routes (cir2 and cir3) do not legally conform and they are defined and used only for the research in the present working package. Some legal requirements concerning the altitude of the test route are given in the Regulation EU 2017/1151, annex IIIa, appendix 7b. These are:

- Moderate altitude below 700 m above sea level.
- Extended altitude conditions 700–1300 m above sea level.
- Start and end points of the trip shall not differ in their altitudes more than 100 m.
- The cumulative positive gain over the entire trip shall be less than 1200 m/100 km.

For the test circles used in the present work, it must be remarked that, principally, the rural part was decisive for the influences of slope and altitude. The city and highway parts were always the same and more or less flat. The variations of altitude have impact on the final results by increasing or decreasing the work amount provided by the vehicle. Figure 11 illustrates the validity check of the three used routes/trips. The trips “cir2” and “cir3” with higher altitude variations do not fulfill entirely the CO₂-normality, exceeding the primary tolerance band of +45(40)/−25% in the middle speed range.

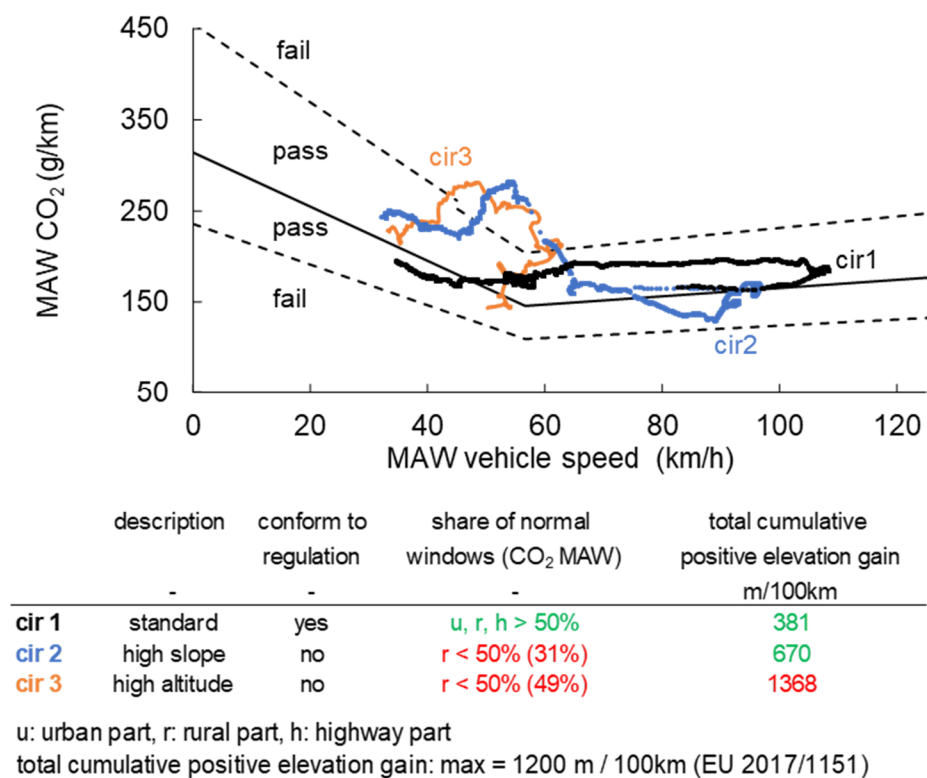


Figure 11. Influence of the varying altitude and slope on the trip validity, gasoline (V1).

The checks of the share of normal windows (r) and of the total cumulative positive elevation gain (in the bottom part of the Figure 11) also show the non-conformity of the trips cir2 and cir3:

- Route cir2 could be accepted for elevation check, but the increase of the CO₂ emissions due to the performed altitude variation leads to a failing CO₂ result (not similar to the WLTC CO₂ emissions).
- Route cir3 shows that both CO₂ emissions and higher altitude variation are beyond the accepted limits.

The altitude data are measured by GPS and verified with topographic map. If the differences between the GPS data and the map is greater than 40 m, the GPS data are corrected. The Figure 12 compares the cumulated emissions CO, NO_x, CO₂, PN of the gasoline car in the three circuits with different slope and altitude. The results concern entire trips, which all were started with cold engine. The higher slope and/or altitude generally increase CO & NO_x, have a slight influence on CO₂, and a negligible influence on PN. (For PN see the very much extended scale of the ordinate).

In order to better discriminate the influences of the altitude and the slope on the emissions, selected parts of trips were taken into consideration. Figure 13 represents the selected segments, all of them with the same driving distance (14.5 km) and with similar average speed (approximately 51 km/h). In this way, the segment chosen from the cir2 represents predominantly the high slope and the segment chosen from the cir3 represents mainly the high altitude. The results of evaluations with this part selection are given in Figure 14. The representation is analogous as in the Figure 12. The statement about increasing the measured emissions by higher slope and/or altitude can be extended to all components. The sharp increases of CO and NO_x in the diagram for cir2 and cir3 can be attributed to the dynamic driving events combined with higher power demand for the slope. Higher slope (cir2) in this comparison needs more energy and emits more CO₂ than the high-altitude profile (cir3).

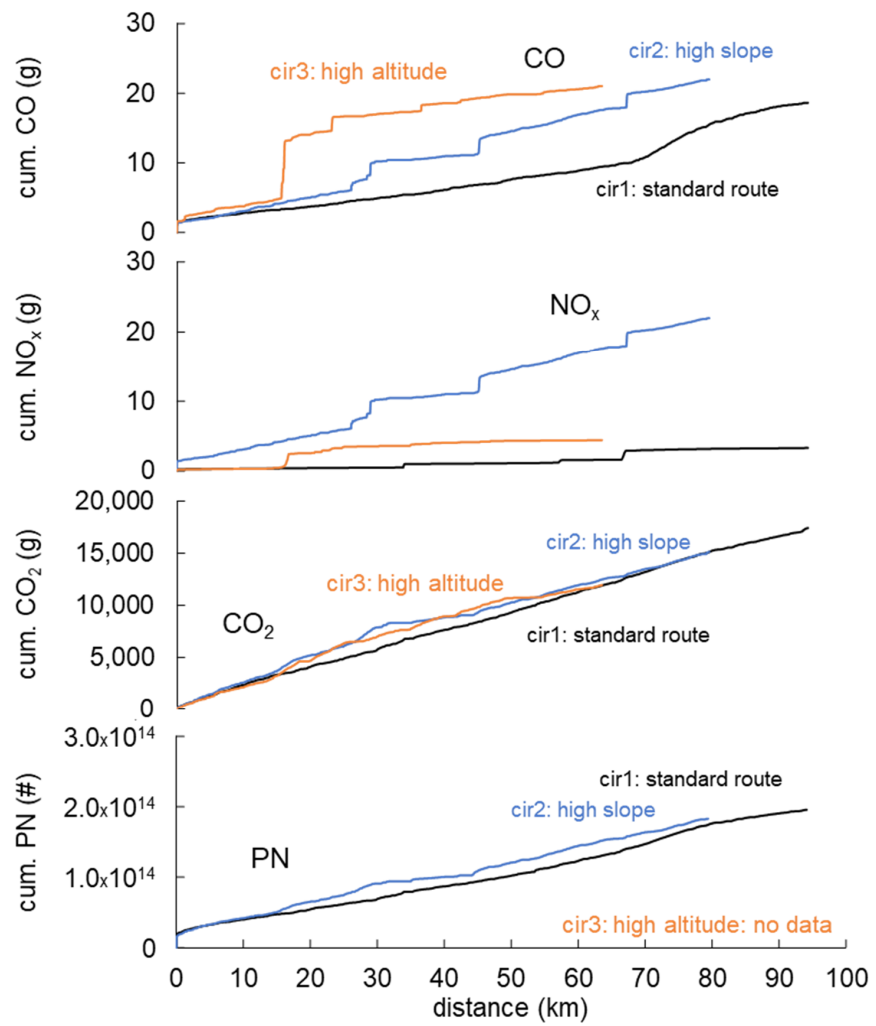
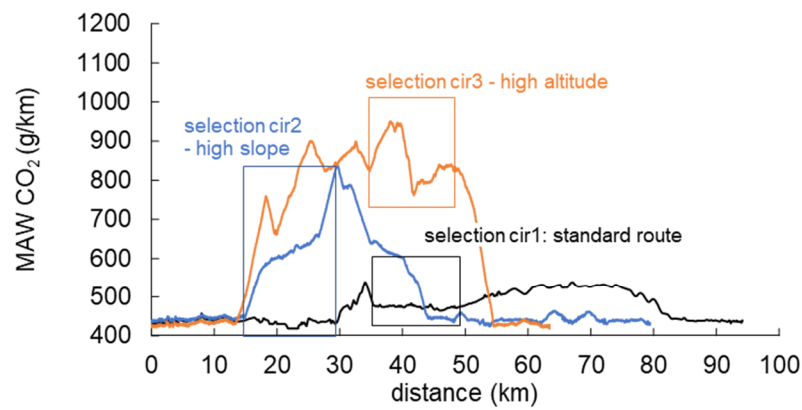


Figure 12. Influences of high altitude and altitude variations on the cumulated emissions, gasoline (V1).



segment of	distance km	vehicle speed average km/h	altitude min m	altitude max m	altitude average m	Δ altitude begin-end m	CO int. mg/km	NOx int. mg/km	CO2 int. g/km	PN int. #/km
cir1	14.5	51.7	464	483	474	5.8	151	7	168	1.5 × 10 ¹²
cir2	14.5	53.1	453	835	613	382	414	130	283	2.8 × 10 ¹²
cir3	14.5	49.1	761	951	850	-4.3	171	49	207	-

Figure 13. Selection of characteristic circuit segments for better visualization of influences of altitude and altitude variations.

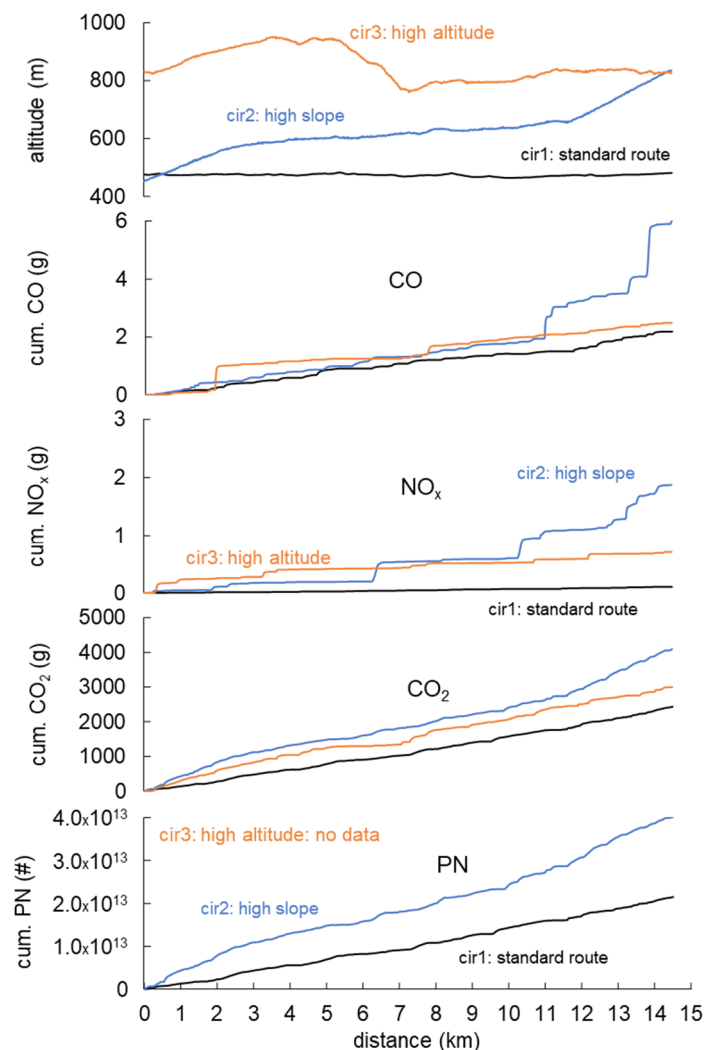


Figure 14. Influences of slope and altitude on the cumulated emissions in the selected parts of the test circuits, gasoline (V1).

4. Conclusions

The different driving conditions in real drive scenarios are ambient temperature (winter/summer), driving style (aggressive/mild), as well as the influence of slope and the altitude. These factors have been evaluated after performing tests in these different extended (non-typical) driving conditions. The expected influences on the individual emissions types could be shown according to the generally valid correlations on how the emission increase or decrease. In the following conclusions can be drawn:

Winter/summer

- For the gasoline vehicle, there are in winter conditions higher values of CO₂ and CO in the total trip. For NO_x and PN, there are no significant differences.
- For the diesel vehicle, the winter-operation increases slightly the CO₂- and NO_x-values. The levels of CO and PN stay unchanged.
- The DPF regeneration increases clearly (both in summer and in winter tests) CO₂-, NO_x-, and PN-values.

Mild/aggressive driving

- The mild and dynamic driving styles have clearly different parameters of the RPA and ($v_{a_{pos}}$); both parameters are higher for aggressive driving.
- During road driving, the parameters of the RPA and ($v_{a_{pos}}$) are for each variant of vehicle and driving style quite repetitive.

- With the diesel vehicle, an excessive driving dynamic, beyond the legal acceptance, was realized.
- The driving style has an influence on the CO₂-normality.
- The DPF regeneration (Diesel) has an influence on the CO₂-normality, which may cause the check to fail.
- The driving style has reproducible effects on the emissions.
- The aggressive driving generally increases the emissions, except PN for gasoline car (*w/o* GPF) and CO for diesel car (DOC + DPF).
- The “dynamic” driving requires more energy, causes higher fuel consumption, and, therefore, higher CO₂-emissions.
- The PN-emissions of the gasoline vehicle (GDI *w/o* GPF) are above, the PN-emissions of the diesel vehicle (with DPF) are below the limit value of 6×10^{11} (#/km).
- There is a higher NO_x-emissions level of the diesel car.

Slope/altitude

- The emissions of CO, NO_x, CO₂, and PN are generally increased by higher slope/altitude.
- The sharp increases of CO and NO_x in the diagrams for cir2 and cir3 can be attributed to the dynamic driving events combined with higher power demand for the slope.
- Higher slope requires more energy and causes higher CO₂.
- The influence on PN is small.

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Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
BFH-TI	Bern University of Applied Sciences, Engineering and Information Technology
CF	Conformity Factor
cir	test circuit
CLD	Chemoluminescence Detector
CPC	condensation particles counter
DC	diffusion charging
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
EGR	Exhaust gases recirculation
EU	European Union
EMROAD	Data processing reference software
FID	Flame Ionization Detector
FOEN	Federal Office of Environment, CH
GDI	gasoline direct injection
GPF	Gasoline particulate filter

GPS	Global Positioning System
GTAA	Granting Type Approval Authority
ICE	Internal Combustion Engine
ISC	in-service-conformity
LD	Light Duty (personal car)
LDV	Light Duty Vehicle
MAW	Moving Average Window
MD	rotating disc minidiluter
NDIR	Non-Dispersive Infrared
NM3	NanoMet3
OBD	On Board Diagnosis
OBS	Horiba on board system
PC	passenger car
PEMS	Portable Emissions measurement system
PN	Particle Number
r	share of normal windows (MAW)
RDE	Real Driving Emission
ResRDE	research of RDE
RPA	Relative Positive Acceleration
SCR	Selective Catalytic Reduction
TC	thermo-conditioner
TWC	Three-way catalyst
V	vehicle
ViPR	volatile particle remover
WLTC	World Light-Duty Transient Cycle
WP	working package

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